

On the PBF neutrino losses in superfluid cores of neutron stars

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Abstract

Axial anomalous contributions into neutrino PBF losses due to triplet pairing of neutrons are still ignored in modeling the evolution of neutron stars. In this paper, the influence of the anomalous axial contributions onto the rate of neutron stars cooling is estimated.

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I. INTRODUCTION

At the epoch of a long cooling, the evolution of a neutron star (NS) surface temperature crucially depends on the overall rate of neutrino emissions from within the star. The cooling dynamics below the superfluid transition temperature is governed primarily by the superfluid component of nucleon matter. The superfluidity of nucleons in NSs strongly suppresses most mechanisms of neutrino emission operating in the non-superfluid nucleon matter (the bremsstrahlung at nucleon collisions, modified Urca processes etc. [1, 2]) but simultaneously strongly reduces the heat capacity and triggers the emission of neutrinos through the neutral weak currents caused by the pair breaking and formation (PBF) in thermal equilibrium.

The theory of PBF neutrino emission via neutral weak currents has a long history. First calculations of the PBF neutrino energy losses were calculated using a vacuum-type weak interactions assuming that the medium effects can be taken into account by introducing effective masses of participating quasiparticles [3, 4]. This resulted to a substantial overestimate of the PBF neutrino energy losses from the superfluid core and inner crust of neutron stars. Only three decades later it has been understood that the calculation of neutrino radiation from a superfluid Fermi liquid requires a more delicate approach.

Within the Nambu-Gorkov formalism the effective vertex of nucleon interactions with an external neutrino field represents a 2×2 matrix in the particle-hole space. This matrix is diagonal for nucleons in the normal Fermi liquid but it gets the off-diagonal entries in superfluid systems [5–7]. The diagonal elements represent the ordinary (dressed) vertices of the field interaction with quasiparticles and holes, respectively, while the off-diagonal elements of the matrix represent the effective vertices for a virtual breaking and formation of Cooper pairs in the external field. In other words, the off-diagonal components of the vertex matrix describe a coupling of the external field with fluctuations of the order parameter in the superfluid Fermi liquid. These so-called "anomalous weak interactions" should be necessarily taken into account when calculating the neutrino energy losses from superfluid cores of neutron stars.

In particular, the anomalous weak interactions are crucial for the neutrino emission caused by the PBF processes. For example, in non-relativistic systems, the ordinary and anomalous contributions into the matrix element of the weak vector transition current mutually cancel, leading to a strong suppression of the PBF neutrino emission [8–10]. Thus, exactly due

to the anomalous contributions the PBF neutrino emission in the vector channel of weak interactions is practically absent. This reflects the well known fact that the dipole radiation is not possible in the vector channel in the collision of two identical particles.

In the case of 1S_0 pairing this has far-reaching consequences. The total spin $\mathbf{S} = 0$ of the non-relativistic Cooper pair is conserved therefore the neutrino emission through the axial-vector channel of weak interactions could arise only due to small relativistic effects [3, 11]. Thus the PBF neutrino energy losses due to singlet-state pairing of baryons can, in practice, be neglected in simulations of neutron star cooling. This makes unimportant the neutrino radiation from 1S_0 pairing of protons or hyperons.

The minimal cooling paradigm [12] suggests that, below the critical temperature for a triplet pairing of neutrons, the dominant neutrino energy losses occur from the superfluid neutron liquid in the inner core of a neutron star. It is commonly believed [13–16] that, in this case, the 3P_2 pairing (with a small admixture of 3F_2 state) takes place with a preferred magnetic quantum number $m_j = 0$. Since the spin of a Cooper pair in the 3P_2 state is $S = 1$ the spin fluctuations are possible and the PBF neutrino energy losses from the neutron superfluid occur through the axial channel of weak interactions. As derived in [17], the neutrino emissivity in this case equals to

$$Q = \frac{2C_A^2}{15\pi^5 \hbar^{10} c^6} \mathcal{N}_\nu G_F^2 p_F M_n^* (k_B T)^7 F_t(\Delta_{\mathbf{n}}/T) , \quad (1)$$

where G_F is the Fermi coupling constant, $C_A \simeq 1.26$ is the axial-vector weak coupling constant of a neutron, and $\mathcal{N}_\nu = 3$ is the number of neutrino flavors; p_F is the Fermi momentum of neutrons, $M_n^* \equiv p_F/V_F$ is an effective neutron mass; the function F_t is given by

$$F_t = \int \frac{d\mathbf{n}}{4\pi} y^2 \int_0^\infty dx \frac{z^4}{(1 + \exp z)^2}. \quad (2)$$

Here the notation is used $z = \sqrt{x^2 + y^2}$ with $y = \Delta_{\mathbf{n}}/T$, where the anisotropic energy gap $\Delta_{\mathbf{n}}$ is given by

$$\Delta_{\mathbf{n}} = \Delta_0(T) \sqrt{1 + 3 \cos^2 \theta}, \quad (3)$$

The unit vector $\mathbf{n} = \mathbf{p}/p$ defines the polar angles (θ, φ) on the Fermi surface.

It is necessary to stress that Eq.(1) involves the anomalous contributions into both channels of weak interactions (vector and axial). A comparison of this formula with the expression that was originally obtained in neglecting the anomalous interactions [4] allows one to see

that the anomalous contributions not only completely suppress the vector channel of weak interactions, but also suppress four times the energy losses through the axial channel. This is an important point which is the subject of the following discussion.

The problem is that the axial anomalous contributions into the PBF neutrino losses due to the triplet-state neutron pairing are still ignored in simulations of the neutron star evolution. The expression for the PBF neutrino losses that is actually used in the simulations (see e.g. [12, 18–20]) is four times larger than that given in Eq.(1).

It is important to notice that accounting of the anomalous contributions only in the vector channel of weak interactions is incorrect in the case of triplet pairing of nucleons. When incorporating the pairing interactions one must consider the modification of the axial-vector vertex to the same order as the modification of the vector vertex is done. In other words, in a consistent approach, the matrix element of the axial current should be calculated with taking into account the anomalous interactions.

The reduction of the PBF neutrino energy losses four times can markedly change a temporal trajectory of the observable surface temperature of the neutron star. The purpose of this paper is to assess the influence of the anomalous axial contributions onto the rate of NS cooling

II. NEUTRON STAR MODEL AND SIMULATION RESULTS

For simulations of the thermal evolution of a spherically symmetric NS I used the NSCOOL code [21] that solves the equations of the heat transport and energy balance in whole GR. In order to study the effects of the suppression of the PBF neutrino emission in the axial channel I use the same NS model which is described in [12] but with a change of reaction constant a_{nt} in Eq. (11) of this work. Namely, I replaced $a_{nt} = 2C_{An}^2$ by $a_{nt} = C_{An}^2/2$ in accordance with the above discussion in order to compare the obtained cooling curves and the curves which was calculated without this change.

To build the non-rotating equilibrium NS, I have solved the Tolman-Oppenheimer-Volkoff relativistic equations of stellar structure (see, e.g., [22]), supplemented by the APR EOS. For the neutron singlet gap I choose the SFB model [23]. For the proton singlet gap I use the CCDK model [24, 25]. Finally, for the neutron triplet gap in the core I consider the TToa model [26].

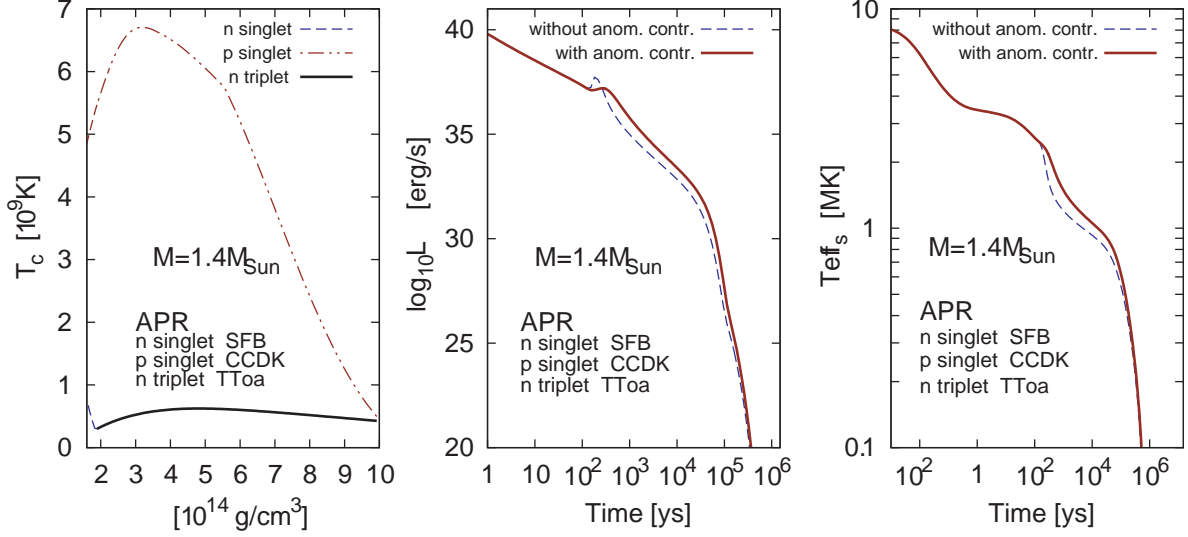


FIG. 1. (Color online) *Left panel:* Critical temperature T_c for neutron superfluidity and proton superconductivity as a function of matter density for the APR EOS. *Middle panel:* The rate of neutrino energy losses from NS. *Right panel:* Non-redshifted surface temperature T_s as a function of the NS age. The NS mass is $M = 1.4 M_{\odot}$ (iron envelope). The lower cooling trajectory was obtained for the case when the anomalous weak interactions are discarded, as it is the case in traditional approach, the upper trajectory was calculated with inclusion of the anomalous terms.

The cooling curves were calculated for a $1.4 M_{\odot}$ NS with iron envelope. In Fig. 1, the left panel shows the critical temperature profiles for neutrons and protons. The right panel demonstrates the non-redshifted effective surface temperature vs the age of the star. The middle panel shows the temporal evolution of total neutrino energy losses from NS.

As expected, we see a splash of neutrino emission once the temperature drops below the critical temperature for the onset of neutron superfluidity. The cooling rate also increases due to the PBF neutrino emission and exponential decrease of the neutron specific heat capacity. It is seen also that the temporal behavior of the curves is different in the two considered cases. The lower cooling trajectory was obtained for the case when the anomalous weak interactions are discarded, as it is the case in traditional approach, the upper trajectory was calculated with inclusion of the anomalous terms.

III. CONCLUSION

Although the deviation of the cooling trajectory does not look very significant (in the logarithmic scale), in fact, it is substantially greater than the experimental inaccuracy in determination of the age and temperature of a neutron star. At least in some cases (see e.g. [20, 27–30]).

It is necessary to note that though all the calculations are made in a frame of the used model and the parameters of the mode are known only in order of magnitude, for example, the critical temperatures for the superfluidity onset. Nevertheless, a more accurate description of the PBF processes can be helpful in a treatment of observations (see e.g. [31]).

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